<u>Hybrid Rocket Based Combined Cycle Test Rig Design, Construction, and Testing</u>

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By
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Hybrid Rocket Based Combined Cycle Test Rig Design and Construction

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An air-augmented rocket engine duct was designed and constructed for testing in the Cal Poly propulsions laboratory to examine effects of secondary burning in a ducted environment. The existing Hybrid rocket test stand was modified so that a duct with an optimized inlet area ratio could be mounted and tests could be performed with varying mixing ratios. The duct and test stand design were modeled in Catia, then parts were purchased for the actual fabrication of the experimental apparatus. Having constructed the air augmented rocket thrust data from the ducted rocket was compared to a non-ducted hybrid rocket and it was seen that there was a slight increase in thrust.

Nomenclature

I. Introduction

Combined cycle rocket performance is of great interest within the propulsion department at Cal Poly. By inducing secondary flow to a high speed rocket exhaust increased thrust especially at low velocities can be achieved. Already a series of experiments and analytical models are being used by student in the Cal Poly Aero department. By conducting an experiment with the hybrid rocket setup, more data can be analyzed to draw further conclusions and reinforce the paralleled experimentation.

NASA development in hypersonics is driven by the fact that for all planetary and Earth orbit missions flight through the hypersonic regime is required. Research focus has then been applied to two missions in which to focus technology and methods development efforts. These two missions include the High Mass Mars Entry Sytems (HMMES) and Highly Reliable Reusable Launch Systems (HRRLS). With deeper examination into the HRRLS it was shown that the reliability of air breathing systems are orders of magnitude better than all-rocket systems[1]. Driving toward hypersonic air breathing systems brings designs toward scramjet and ramjet propulsive systems but for these systems to work efficiently high mach numbers are needed. To get to these high mach numbers air augmented rockets have been shown to be a viable option to power the launch system into the high mach numbers to operate ramjet and scramjet technology. Air augmented rockets work by using a shrouded rocket or "ducted" rocket in which the rocket plume would act as the primary flow which would entrain atmospheric condition secondary flow introduced through ducts. The air augmented rocket would produce more thrust by entraining the secondary flow and introduce more oxidizer into the rocket exhaust which could allow for more complete combustion of the exhaust. The use of the air augmented rocket within the hypersonic vehicle is known as a rocket based combined cycle and can create air breathing launch vehicle options that increase reliability and drive down cost[2].

For many years jet ejectors, which in concept are very similar to air augmented rockets, have been used in the commercial and industry setting. Examples include the use as scavenging pumps in the fuel tanks of commercial airliners or in the application of jet ejectors in industrial applications to manage steam pressures[3]. However the jet

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ejectors used in these applications are designed for very specific operating conditions. These jet ejectors also operate with the use of pressurized air or steam as the primary flow rather than a rocket exhaust. Because the operation and design of these jet ejecting devices are so specific the extrapolation of data from their operation cannot be used to determine the performance of more general air to air ejectors where operating pressures can vary, such as in the missions of launch vehicles. This drives the resurgence in testing of air/air ejectors and in this case air augmented rockets to determine how these pressure variations in both secondary and primary flow can change performance.

This experiment takes the existing hybrid rocket experiment[2] from the Cal Poly propulsion lab and alters the rocket to fire within a duct. This essentially makes an air augmented rocket by placing the primary rocket exhaust flow within the duct. The primary flow of the rocket plume pulls in secondary flow, at atmospheric conditions, into the duct through space between the rocket and the duct as shown in Fig. 1.

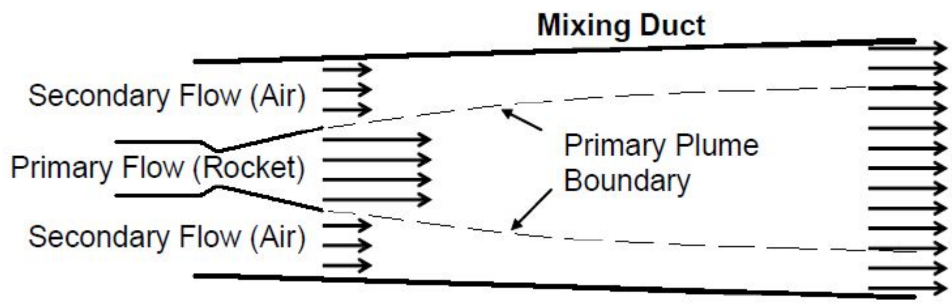

Figure 1. Air augmented rocket

Primary flow comes from a polymethylmethacrylate-oxygen hybrid rocket and then secondary flow is entrained and mixed in the duct before exiting the duct. Also the introduction of more oxygen by the secondary flow allows for the possibility of secondary ignition. To provide an ignition source for possible secondary combustion a butane torch was attached to the duct and introduces a flame into the rocket exhaust. Using this set up, procedures used for the hybrid rocket experiment can be slightly modified allowing reproducibility close to that of the already well developed and significantly tested hybrid rocket experiment. Thrust values from the air augmented rocket are then compared to the thrust values found from extensive testing of the hybrid rocket experiment set up. Through the comparison of these two values the effect of the duct on rocket performance can be determined.

II. Design Methodology

A. Existing Equipment

The existing hybrid rocket test stand shown in Fig.1 is used in various experiments including an AERO 401 laboratory exercise. The rocket motor is comprised of a polymethylmethacrylate fuel rod approximately 9 inches in length and 2 inches in diameter. The inner wall is the site of the combustion reaction which creates thrust. The oxidizer used is pure oxygen ranging in pressures from 60-120psia. The reaction is induced with a propane mix that is ignited by a spark plug, and once lit is switched over to the pure oxygen.

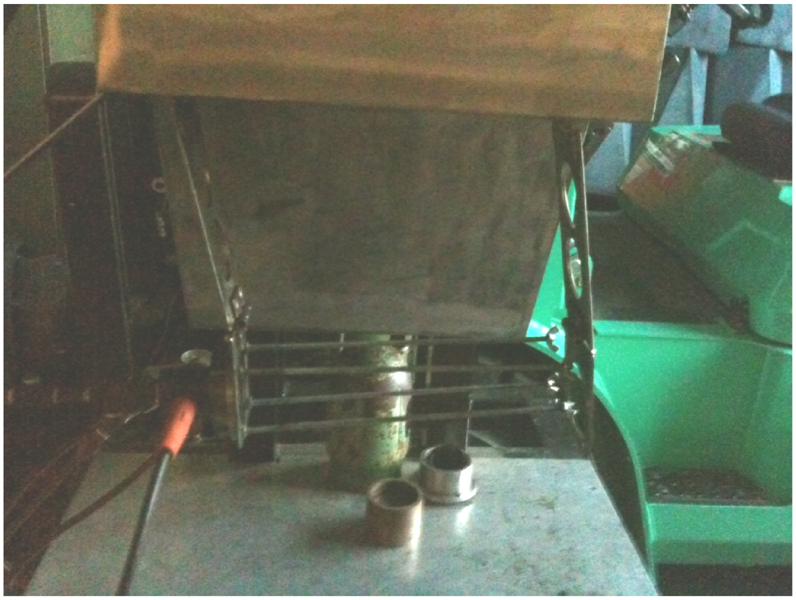

Figure 2 Existing Hybrid Rocket Test Stand

B. Duct Design Considerations

The duct modification had to be designed such that it would not permanently affect the normal operation of the hybrid rocket experiment during class use. This presented an interesting challenge addressed with some creative solutions.

First, a new motor mount had to be designed to hold the fuel rod, nozzle, and ducting. This motor mount also had to allow the motor to move freely for accurate thrust measurements and still be structurally supportive. Additionally, effort had to be made to ensure the parts would actually be manufacturable and that the pieces could actually be assembled without custom tooling and machining. This was perhaps the most challenging design consideration because of the complex inner duct structure that needed to house the nozzle, motor mount, and duct mount. This resulted in an inner motor housing that could be assembled independent of the duct and then allowed for accessible attachment mount to fasten the duct on and house the nozzle. The inner motor housing is seen in Fig. 3.

Figure 3 Inner Motor Housing for RBCC Modified Rocket

C. Duct Design

The design of the duct started with research of previous experiments involving combined cycle rockets for how they were constructed. This would also give the dimensions for optimum mixing of the secondary flow. Additionally, dimensions were taken from the existing hybrid rocket test stand to ensure proper compatibility.

The duct, test stand, and motor housing assembly was then drawn in a solid modeling program. This can be seen in Fig. 4 and Fig. 5.

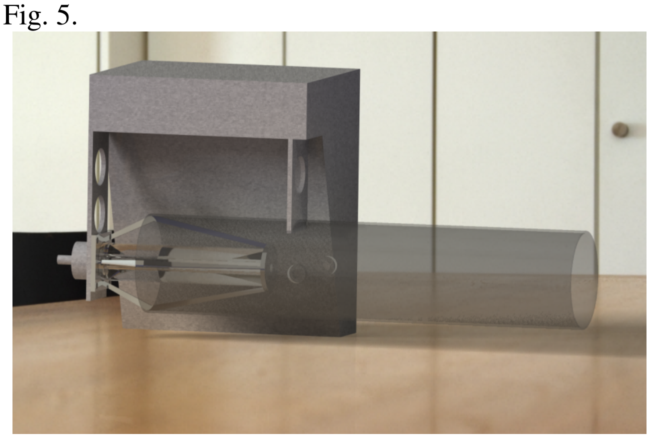

Figure 4 Solid Model of Hybrid RBCC Duct

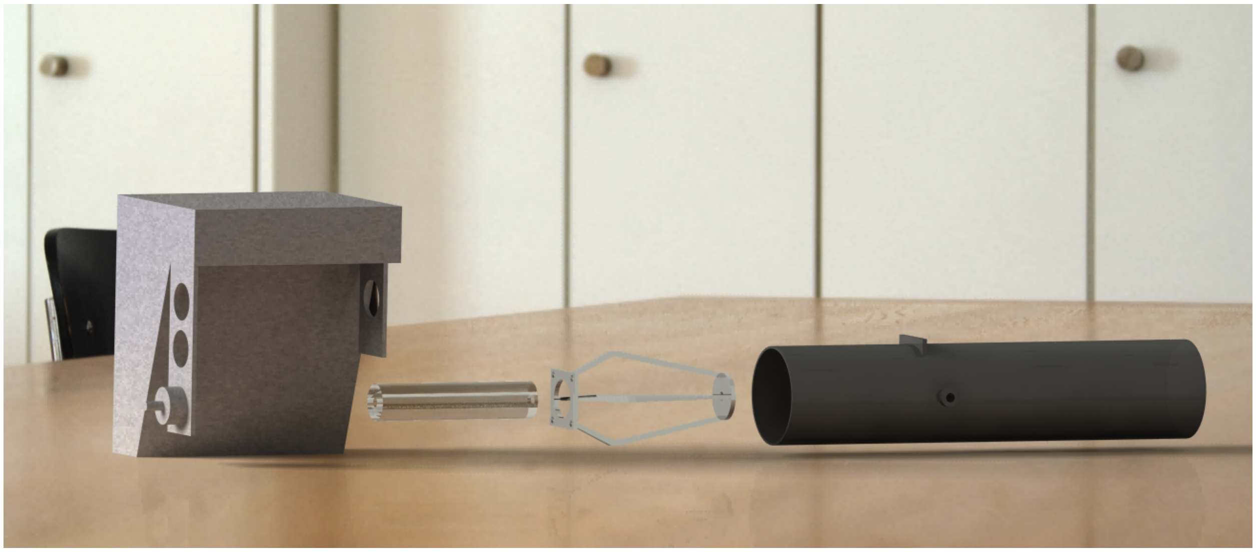

Figure 5 Exploded View of Solid Modeled Hybrid Rocket and Duct

Fig. 5 is an exploded view showing explicitly the test stand, fuel rod, motor mount, and duct system.

Because of the nature of the solid rocket fuel, it was determined that there needed to be a source of re-ignition downstream in the duct once unburnt fuel has been mixed with secondary flow. To solve this dilemma, a blowtorch was installed downstream of the nozzle perpendicular to the flow as to not influence thrust reading.

III. RBCC Fabrication

A. Parts Acquisition

Taking parts drawing from the solid model design, a parts list was created with the necessary materials to construct the test apparatus. The assembly involved cutting and welding of the plain steel stock. Steel was chosen because of its relative inexpensiveness and ease of fabrication, especially for the welded components.

B. Construction

The parts were cut and assembled in the Cal Poly Aero hangar using the machine shop available for student projects. Fig. 6 shows the duct and motor housing assembled with the flameholder blowtorch attached.

Figure 6 Duct, Motor Mount, and Flameholder Assembled

Fig. 7 shows a detailed close up of how the fuel rod is integrated into the modified motor mount and duct assembly.

Figure 7 Fuel Rod Integration Close-Up

C. Test Stand Mounting

Because much thought was put into how the assembly would be implemented with minimal modifications, the installation of the secondary duct and motor mount was relatively uneventful. The rear motor mount hanger was removed and the hangar attached to the duct was mounted. Also, the long threaded rods used for the original rocket setup were extracted and replaced with shorter screws for ease with the new motor mount. The competed assembly can be seen in Fig. 8.

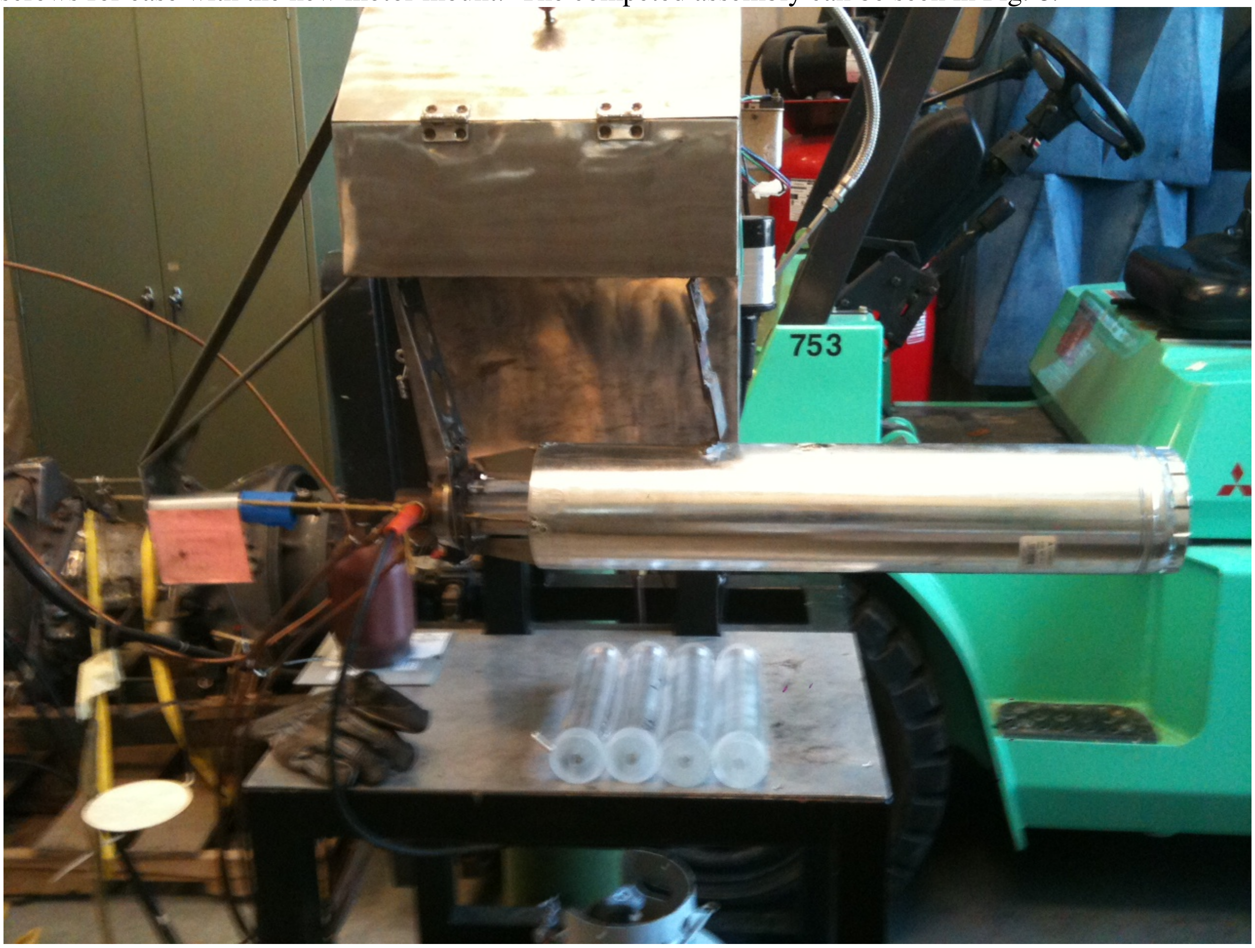

Figure 8 Installed Motor Mount and Duct on Test Stand

The unit was successfully mounted and no permanent modifications to the existing test stand were necessary meaning this was a completely reversible process.

I. Apparatus and Procedure

The experiment was conducted using the Cal Poly Propulsions Laboratory. The fuel grain used is a 2 inch diameter, 9 inch long polymethylmethacrylate. The test stand used to hold the fuel grain consists of a swing that allows the motor to push on a load cell to measure thrust force, an inlet oxygen line, an inlet propane line, a spark plug, an inlet nozzle for the oxygen, and a carbon exhaust nozzle. The load cell is connected to a 16-bit DAC device hooked into the lab computer to record thrust values in LabView. The propane tank, oxygen tank, and spark plug are all controlled by solenoids that are operated from a control panel inside the control room adjacent to the test area. There are also pressure sensors before and after the oxygen inlet nozzle that provide readings to the control panel inside the control room. The experimental apparatus is depicted in Fig. 9.

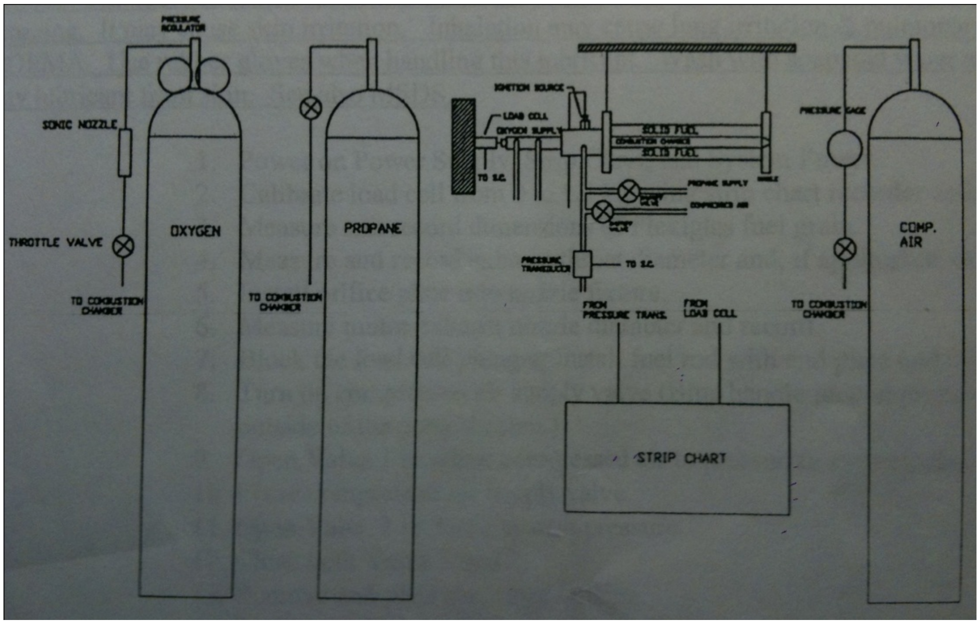

Figure 9 Hybrid Rocket Experimental Apparatus

The first step in the experimental procedure is to prepare the lab. The doors are opened to vent exhaust and the lines are verified to be hooked up correctly to their respective valves. The load cell is calibrated by recording output voltages of varying masses from 200g to 1200g in increments of 200g. The slope of the line is used to calibrate the load cell so the equation in LabView outputs to pound-force. This also verifies that LabView and the load cell are operating correctly and have linear force outputs. Next, the fuel grain's inner diameter, outer diameter, length and mass are recorded. The apparatus is pressure tested by coating each end of the fuel tube with grease, installing an O-ring and flat disk to one end and mounting the fuel tube to the apparatus with the 4 screws. The oxygen tank valve is opened to 100psi and the set up is checked for leaks. Once everything is satisfactory, without leaks, the flat disk is replaced with the carbon nozzle and the fuel tube is re-mounted. In preparation for the test run, the oxygen tank valve is set to the test pressure, the propane tank valve is opened completely, and the protective sheath is removed from the load cell. Once the area is cleared of occupants, the LabView data begins recording and the switches activating the oxygen and propane valves are flipped while the spark plug runs to ignite the reaction. The rocket motor is timed for 10 seconds and then the valves are closed to end the run. When the lab clears of fumes, the valves on the propane tank and oxygen tank are shut off, the load cell sheath is replaced and the fuel tube is removed from the test stand. This experiment is repeated with two runs at each oxygen pressures of 60psi, 80psi, and 100psi.

I. Analysis

Analysis

The data collected in LabView was processed through MATLAB for analysis. After removing excess noise and outliers from the data, the thrust traces showed a consistent trend as seen in Fig. 10-12.

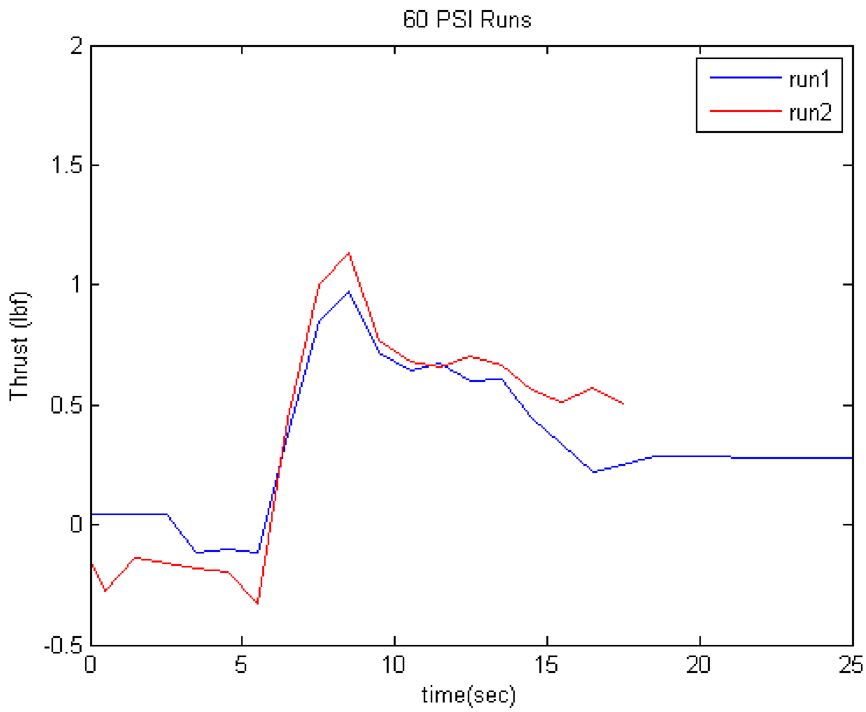

Figure 10 60 PSI Runs

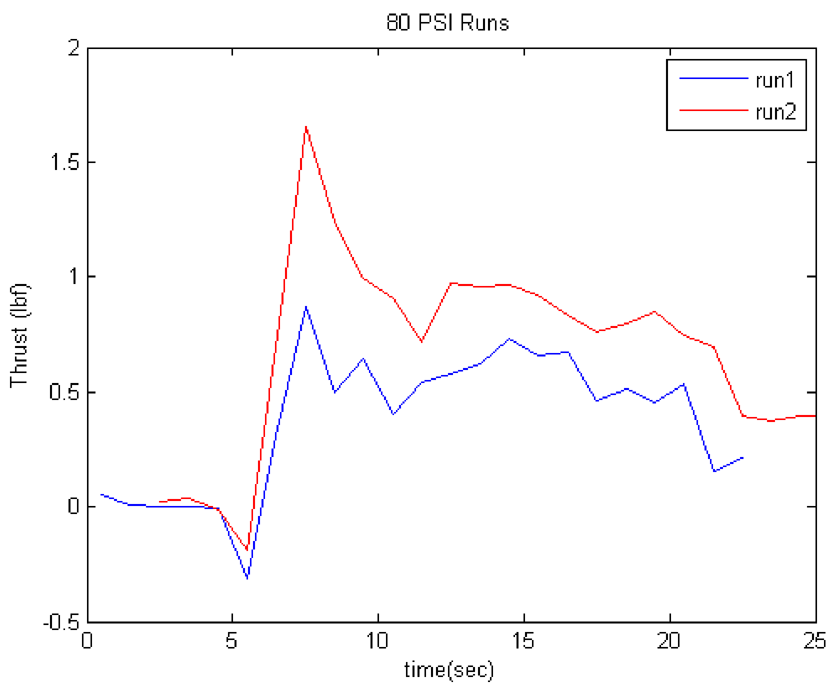

Figure 11 80 PSI Runs

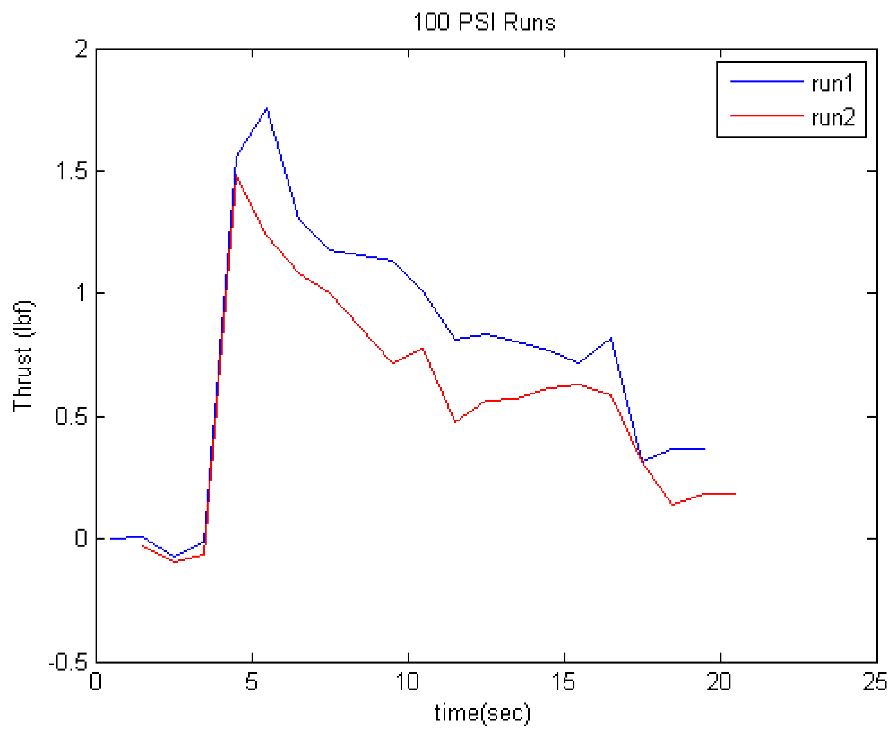

Figure 12 100 PSI Runs

All of the thrust traces show the same general trend of a negative thrust pressure followed by a peak and a tapering off for the next 10 seconds. The initial negative thrust value is most likely due to the inflexible brass oxygen and propane lines becoming pressurized, placing a slight strain on the experimental apparatus and affecting the tare reading of the load cell.

The peaks of each thrust trace occur during the transition from propane and oxygen to just pure oxygen. The added propane fuel creates a high peak thrust that tapers after the propane is shut off. These peaks are fairly consistent within each pressure setting except for in the 80 psi case. This is because the oxygen cylinder used ran out of pressure during the 1st run at 80 psi, leaving a much lower thrust value.

The fluctuations in the remaining portions of the runs were visibly reinforced by the inconsistent burning observed during some of the runs. This could be caused by some excessive wind that was present in the test cell during the experimental runs. The variation in flow in and out of the duct due to wind could heavily influence thrust readings of this magnitude.

Next, a trend was found through the variation in fuel-air mixture as shown in Fig. 14. Here we can see the strong trend of an increase in thrust as the oxygen chamber pressure is increased. This means as the fuel-air mixture is leaner, the Hybrid RBCC setup achieved better performance. This is as expected because as more oxidizer is presented in the flow more propellant can be burned and the thrust can increase. However in comparison to the hybrid rocket experiment without a duct the thrust at each respective pressure increased by around 0.1 lbs as can be seen by comparing Fig. 14 to Fig. 15 at the respective pressures. Fig. 15 is thrust versus average chamber pressure but the oxygen chamber pressure is listed next to each respective point. The most likely reason for this increased thrust is induced secondary flow. With the increased velocity of the rocket exhaust the pressure within the mixing tube begins to drop and ambient pressure air begins to enter into the mixing tube. This air entering the mixing tube adds mass to the exit flow and the thrust increases. Unfortunately the exact amount of secondary flow entering the mixing tube cannot be determined with the experimental setup used. For adequate mixing and to use the theoretical equations derived for air augmented rockets a mixing tube length of about 7 times the diameter of the duct is needed. Our experimental duct length was about 3 times the diameter of our mixing duct due to the fact that using a mixing duct length of 7 times our diameter would not have been possible to attach accurately with our limited experience in fabrication and assembly of tests. Because of this it can't be assumed that there is saturated supersonic flow and that the secondary flow is being choked. Since this is the case the mach value of the secondary flow cannot be assumed to be 1 and Eq. 1 and Eq. 2 cannot be solved without determining pressure and temperature readings throughout the duct to determine the Mach number.

$$\mu = (\lambda' - 1) * \frac{P_i^"}{P_i'} \frac{M_{*1}^"}{M_{*1}'} * \left(\frac{m^2 - M_{*1}^{"2}}{m^2 - M_{*1}'^2}\right)^{\frac{1}{\gamma - 1}} \left(\frac{T_i'}{T_i^"}\right)^{3/2} \tag{1}$$

$$\bar{\omega} = \frac{P_1^"}{P} * \left(\frac{m^2}{m^2 - M_{*1}^{"2}}\right)^{\frac{\gamma}{\gamma - 1}} \tag{2}$$

λ' is a geometric definition that can be seen in Fig. 13.

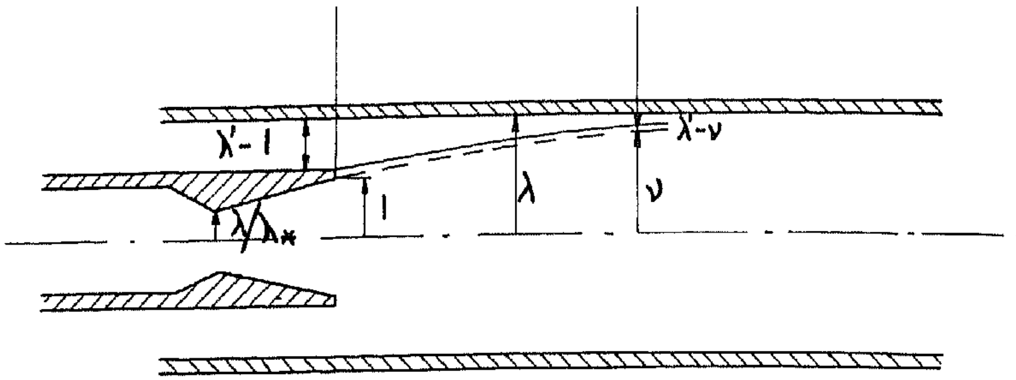

Figure 13. Air augmented rocket key dimensions

In both of these equations the " stands for the secondary flow and ' stands for the primary flow. The "i" subscript is for stagnation condition and M_{*1} is the mach number of the respective flows at the exit of the primary exhaust location. P and T are pressure and temperature respectively and γ is the specific heat of both flows as they are assumed to have the same specific heat. Symbol "m" is defined by Eq. 3.

$$m^2 = \frac{\gamma + 1}{\gamma - 1} \tag{3}$$

The symbol "μ" is the ratio of the secondary mass flow rate to the primary mass flow rate and "ω" is the secondary stagnation pressure to the exit pressure. If the mixing duct was correct and we could correctly assume that the secondary flow had been choked then these equations could be used to determine the amount of additional mass flow that had been added and by using this along with the known primary mass flow and exit velocity a theoretical thrust could be determined.

Even though the results of this experiment are not completely conclusive it was a very good learning experience and shows that there is some benefit to adding a duct since the average thrust at each pressure setting raised. With a more advanced experimental setup in which the secondary mass flow rate along with pressures throughout the mixing tube could be determined and a way of putting the correct length mixing tube on the stand could be determined theoretical values can be compared against measured for a realistic air augmented hybrid rocket.

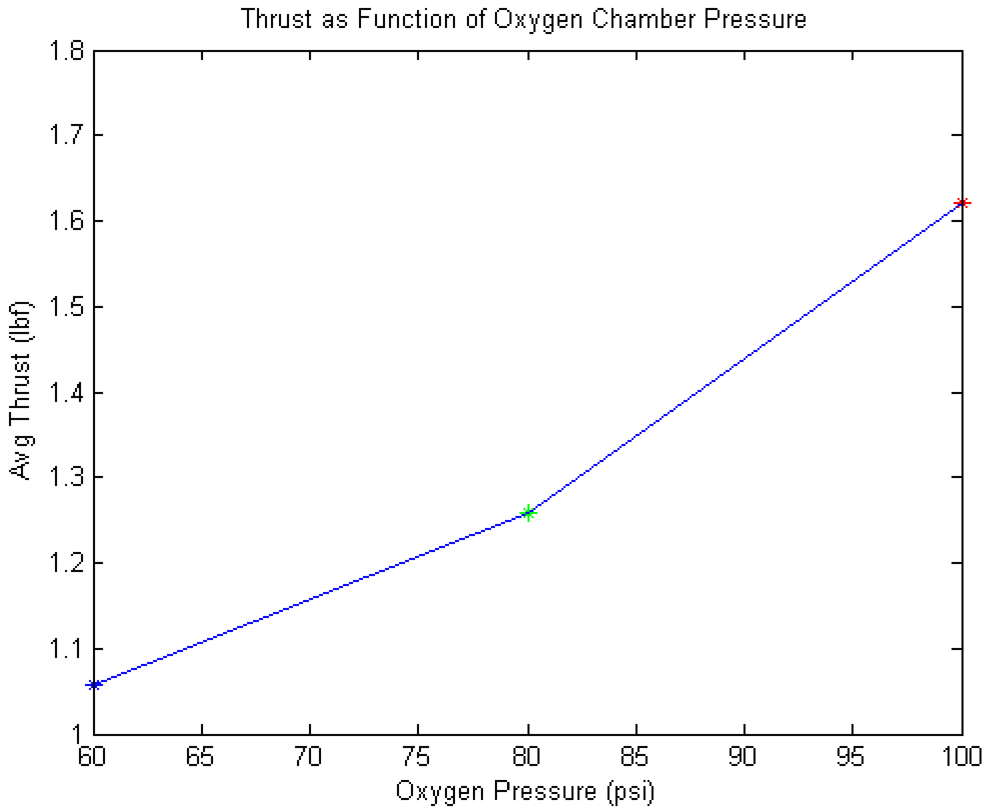

Figure 14 Thrust as a Function of Oxygen Chamber Pressure (with duct)

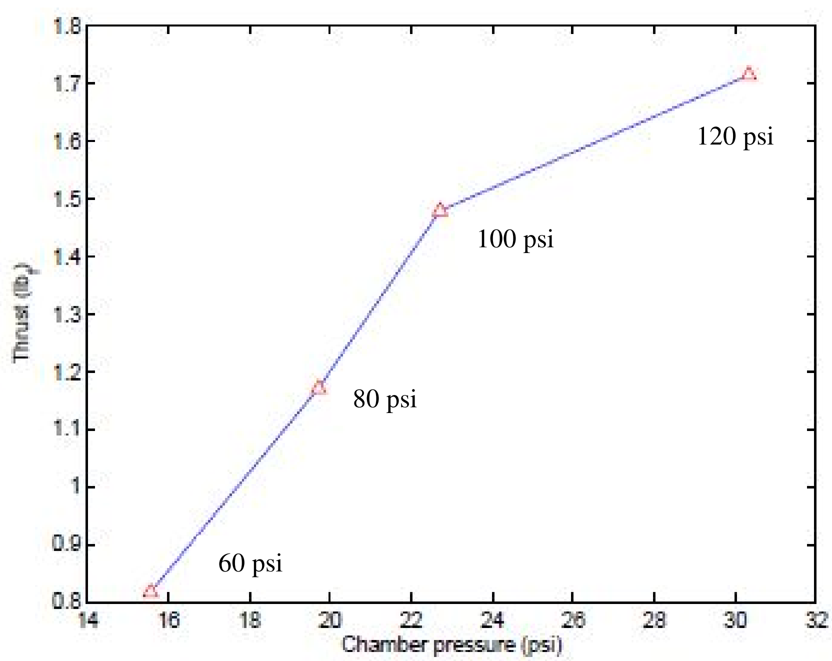

Figure 15 Thrust as a Function of Average Chamber Pressure (no duct)

IV. Conclusions

A combined cycle hybrid rocket would be desirable in a variety of applications. By improving the already favorable performance of hybrid rockets with a ducting system, new propulsion methods for transonic and hypersonic vehicle could be implemented. The experiment conducted modified the existing hybrid rocket test stand with a duct for inducing secondary flow. Testing revealed that a lean fuel-air mixture provided best performance, likely because of more fuel being burnt quicker producing a higher mass flow rate and resultant thrust. It was also realized that our experimental setup did not have enough measurements to directly compare to previous air augmented rocket experiments. Pressure transducers would be needed throughout the duct to characterize the secondary and primary flow mixing throughout the duct. Also pressure transducers to measure the exact pressure at the primary flow throat along with the ability to monitor and measure secondary flow pressure would be very beneficial but require a much more advanced setup. In our experiment configuration only the overall thrust could be compared and not much can be done to show the effect of mixing and duct length. By comparing the thrust from the hybrid rocket experiment to our modified ducted hybrid rocket we saw some gain in thrust and this gain in thrust in promising for further experiments. Continued advancement of this experiment can show more conclusive results and the idea of running an air augmented hybrid rocket matches with NASA goals for cheaper, more reliable launch vehicles and shows much application.

V. References

[1]Fabri, J. & Siestrunck, R., “Supersonic Air Ejectors”, Advances in Applied Mechanics, Vol. 5, pgs. 1-33, 1958

[2]Unknown, \AERO 401 Laboratory, Hybrid Rocket Experiment." California Polytechnic State University Aerospace Engineering Department.

[3]Gist, D. R., Foster T. J., DeTurris D. J., “Examination of Fabri-Choking in a Simulated Air Augmented Rocket” California Polytechnic State University Aerospace Engineering Department

[4]Tillman, T. G., and W. M. Precz. "Thrust Characteristics of a Supersonic Mixer Ejector." *Journal of Propulsion and Power* 11.5 (1995): 931-37. Print.

[5]Foster, T. J., Gist, D. R., and DeTurris D. J., “Methane/GOX Air Augmented Rocket Plume Testing” California Polytechnic State University Aerospace Engineering Department.